

## PERFORMANCE EVALUATION OF A KINESTHETIC-TACTUAL DISPLAY

Richard J. Jagacinski, John M. Flach, and Richard D. Gilson  
Associate Professor, Graduate Student, and Professor  
The Ohio State University  
Columbus, Ohio

Richard S. Dunn  
Engineering Psychologist  
U. S. Army Research and Technology Laboratory  
Moffett Field, California

### Abstract

Simulator studies demonstrated the feasibility of using kinesthetic-tactual (KT) displays for providing collective and cyclic command information, and suggested that KT displays may increase pilot workload capability. A dual-axis laboratory tracking task suggested that beyond reduction in visual scanning, there may be additional sensory or cognitive benefits to the use of multiple sensory modalities. Single-axis laboratory tracking tasks revealed performance with a quickened KT display to be equivalent to performance with a quickened visual display for a low frequency sum-of-sinewaves input. The trackers approximated a lag in these tasks. In contrast, an unquickened KT display was inferior to an unquickened visual display. The trackers approximated a proportional element in these tasks. Full scale simulator studies and/or inflight testing are recommended to determine the generality of these results.

### Introduction

The kinesthetic-tactual (KT) display has been under development and evaluation since 1966. It provides a useful display alternative for helicopter tasks which have high visual workload or which are incompatible with visual or auditory display devices. Examples include terrain flight with high demands for visual attention outside the cockpit and night flight with viewing aids which are not fully compatible with cockpit visual displays. Numerous laboratory and simulation studies have been conducted to develop prototype KT displays and to measure performance with these displays. These studies show the concept to be feasible for helicopter application and effective at visual workload relief. This report first summarizes some early studies oriented to workload and feasibility issues, and then discusses some data which provide more detailed quantification of KT display performance.

The KT display was invented by Dr. Robert Fenton of the Ohio State Department of Electrical

Engineering. In a series of studies<sup>1,2,3</sup> he and his colleagues demonstrated the display's usefulness in improving the precision with which car drivers could control the distance between themselves and a vehicle in front of them.

An example of a single dimensional KT display as it might be used on a helicopter collective handgrip is shown in Fig. 1. An electromechanical slide protrudes from the surface of the handgrip to indicate the direction and magnitude of tracking error. If there is zero error, the slide is flush with the handgrip. If the slide protrudes downward, the pilot moves the collective in the downward direction until the slide returns to the flush position.

A two-dimensional KT display as might be used on a helicopter cyclic handgrip is shown in Fig. 2. The electromechanical slide is in the form of a ring that is flush with the control grip when there is zero tracking error. The protrusion of the ring from the control grip represents a vector composite of lateral and longitudinal errors. The appropriate response is to move the cyclic in the direction of the protrusion until the ring is again in the flush position. The vectoral nature of this display seems to be highly compatible with the two dimensional cyclic movement.

### Fixed Wing Aircraft Study

One use of the KT display has been to provide pitch commands in fixed wing aircraft. Gilson and Fenton<sup>4</sup> measured the performance of novice pilots in a Cessna 172 with three different types of displays: (1) a visual display of airspeed; (2) a visual display of deviations from a desired angle of attack; (3) a KT display of deviations from a desired angle of attack. The KT display was mounted on the control yoke handle, and pilots minimized protrusion of the display from its zero error position with fore-aft movements of the yoke. For controlling angle of attack in an approach to landing maneuver, the visual and tactual displays of angle of attack were comparable to each other, and both were superior to the visual display of airspeed. In a tight turn about a point at constant speed and constant altitude, the KT display

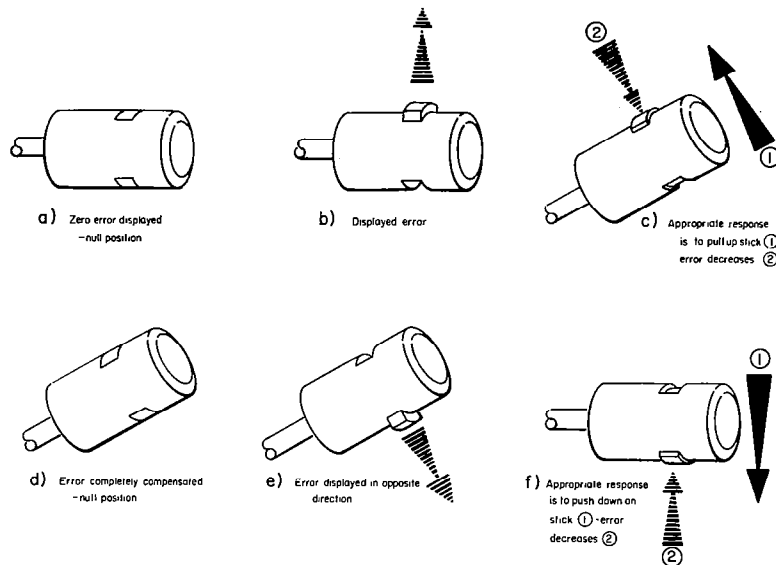


Fig. 1 Control-display relationship for a one-dimensional kinesthetic-tactual display suitable for a helicopter collective. (Copyright 1979, Human Factors, Vol. 21, p. 80)

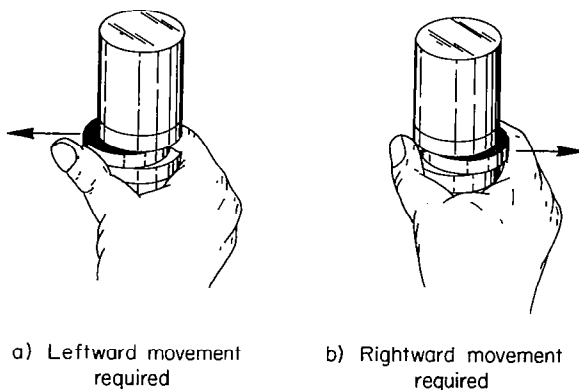


Fig. 2 Control-display relationship for a two-dimensional kinesthetic-tactual display suitable for a helicopter cyclic.

permitted superior performance to the two visual displays in controlling angle of attack, altitude, and airspeed. This latter maneuver requires considerable monitoring of visual cues outside the cockpit. The reduced need for visual scanning with the KT display may account for these results.

#### Helicopter Simulation Studies

Two helicopter simulation studies were conducted using the Tactical Avionics System

Simulator (TASS) facilities at the U. S. Army's Avionics Laboratory, Fort Monmouth, New Jersey. The first study by Gilson, Dunn, and Sun<sup>5</sup> investigated performance of an instrument flight rules decelerated landing maneuver in a simulated UH-1 helicopter buffeted by wind gusts. Cyclic commands were indicated visually by horizontal and vertical crossbars; pedal commands were indicated visually by a rate of turn needle. Collective commands were presented either visually by a display similar to a glide slope pointer on the left-hand side of the flight director, or tactually by a single dimensional KT display mounted on the handgrip of the collective. Experimentally it was possible to make the overall task more difficult by adding a time delay to the cyclic roll dynamics. Adaptive circuitry adjusted this time delay so that the sum of absolute tracking errors of the four command signals reached a criterion value. The performance measure was the value of the time delay necessary to achieve this error criterion. For all five pilots in this study, the KT display permitted a longer time delay than the visual display. The superiority of the KT display may be due to reduced visual scanning or a more cognitive advantage regarding how the pilot processes information from multiple modalities. This issue was addressed in a later laboratory study.

A second helicopter simulation study by Sun<sup>6</sup> examined the feasibility of tactually providing both collective and cyclic commands while still providing other visual information, e.g.,

situational displays. The simulated helicopter was a UH-1. A single axis KT display was mounted on the collective handgrip as in the previous study. Additionally, a two dimensional KT display in the form of a ring was mounted on the cyclic handgrip. A nonlinear gain was used to magnify the protrusion of the ring for small tracking errors. Wearing flight gloves, pilots were able to use these KT displays to successfully perform an instrument flight rules decelerated landing maneuver. With pitch and roll rate signals used to quicken the cyclic display, pilots were also able to maintain a stable hover in the presence of simulated wind gusts, and concurrently perform a secondary light-cancelling task.

#### Recent Laboratory Studies

##### Single-Axis Tracking

In a recent laboratory study at The Ohio State University by Jagacinski, Flach, and Gilson,<sup>7</sup> student subjects were trained on a critical tracking task using one-dimensional visual or KT displays with or without quickening. A critical tracking task<sup>8</sup> requires subjects to stabilize the output of a first-order unstable system. Any unsteadiness in the subject's hand movements excites the instability and in turn requires corrective stabilization by the subject. The difficulty of this task is determined by the time constant of the unstable system. The shorter the time constant, the more rapidly the unstable system tends to exponentially amplify small deviations from the desired constant

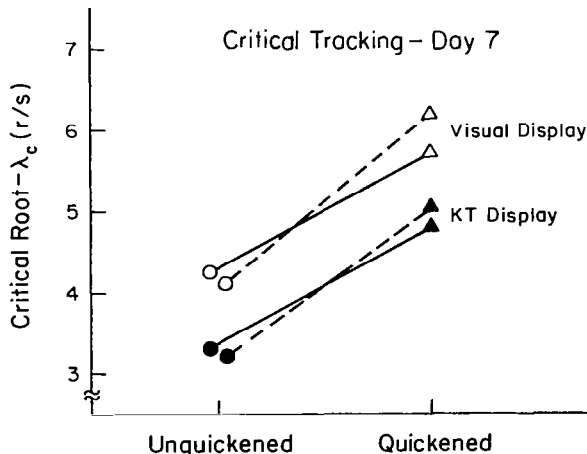


Fig. 3 Critical tracking scores for eight groups of four subjects. Groups connected by dashed and solid lines were respectively transferred to stationary tracking with system dynamics 1.5/s and 3.0/(s-1).

output. In a critical tracking task adaptive circuitry gradually shortens the time constant until the task becomes so difficult that the subject loses control. The inverse of this critical time constant at the instant control is lost is called the critical root, and is represented with the symbol  $\lambda_c$ .

In this experiment, the single dimensional KT display was mounted on a control stick similar to a helicopter collective. The visual display consisted of a vertically moving line on an oscilloscope screen. The quickened signals consisted of a simple addition of error and error velocity with the two equally weighted. The group means of the critical roots are shown in Fig. 3. These results replicate the basically additive effects of modality and quickening previously found by Jagacinski, Miller, and Gilson.<sup>9</sup> The visual modality was superior, and the quickened displays were superior. However, the quickened KT display was approximately equivalent to the unquickened visual display.

Following the critical tracking, subjects were transferred to a stationary compensatory tracking task in which they used the same displays. The input was a sum of nine sinewaves with the amplitudes of the three lowest frequency sinewaves (.35, .73, 1.08 r/s) five times greater than the amplitudes of the other sinewaves.

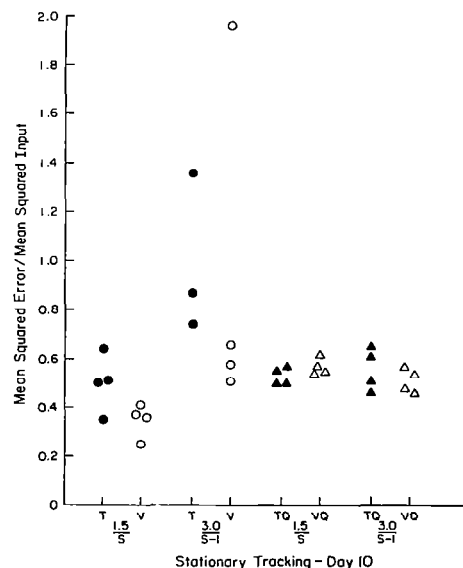


Fig. 4 Mean squared error normalized by mean squared input for thirty-one individual subjects. The symbols represent the same display conditions as in Fig. 3.

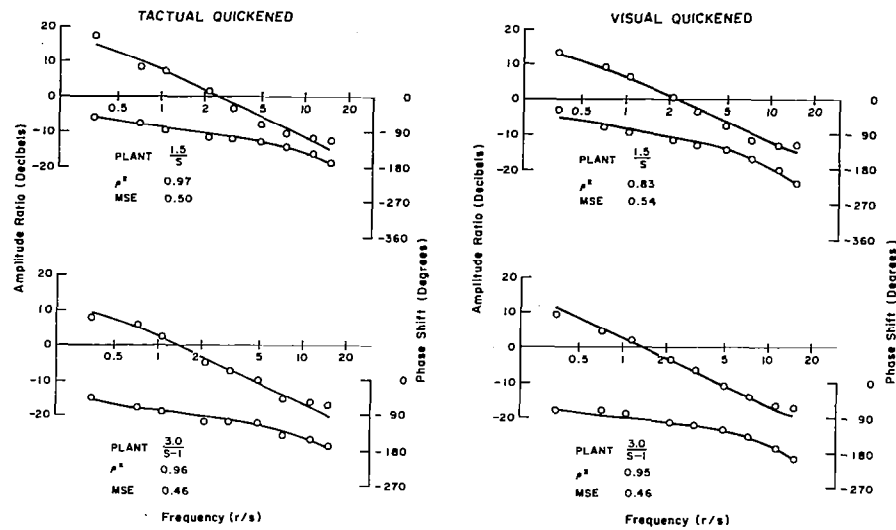


Fig. 5 Linear transfer functions for the subjects with the lowest mean squared error in each of four quickened display conditions. The circles indicate the data points, and the solid lines represent analytic approximations consisting of a low frequency lag, a high frequency lead, a gain, and a time delay.

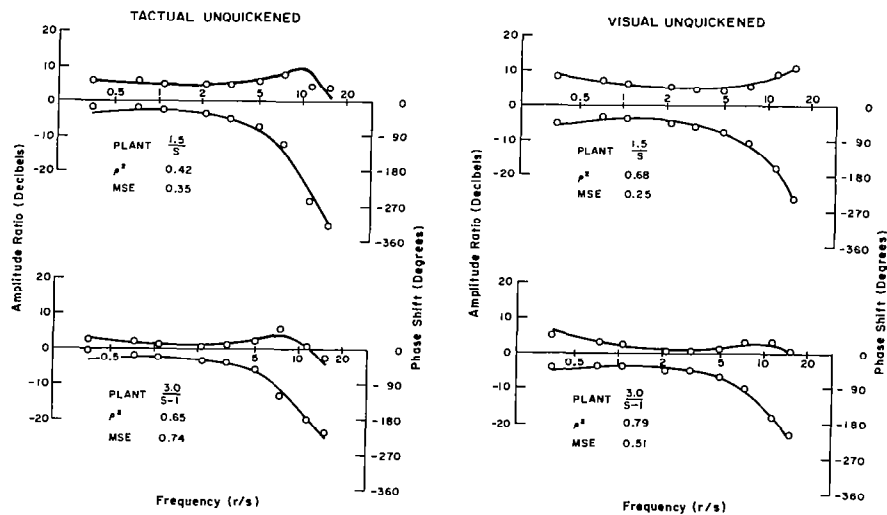


Fig 6 Linear transfer functions for the subjects with the lowest mean squared error in each of four unquickened display conditions. The circles indicate the data points, and the solid lines represent analytic approximations consisting of a low frequency lag and lead, a high frequency second-order lag, a gain, and a time delay.

Half the subjects controlled a single integrator system ( $1.5/s$ ), and half controlled a first-order unstable system ( $3.0/(s-1)$ ). Mean squared error scores are shown in Fig. 4. The unquickened visual displays were superior to the unquickened tactual displays. The quickened visual and tactual displays produced equivalent error scores.

Describing functions were calculated for each subject. For the quickened displays subjects were well approximated by a low frequency lag, a high frequency lead, a gain, and a time delay. As shown in Fig. 5, the describing functions were very similar for the tactual and visual displays and accounted for about 90% of the variance in the subjects' control movements ( $\rho^2$ ).

For the unquickened displays, subjects were approximated by a low frequency lag and lead, a high frequency second-order lag, a gain, and a time delay (Fig. 6). Overall the linear transfer functions for the visual and KT displays were very similar. Subjects using the KT display did, however, exhibit less low frequency phase lag. About 60-70% of the variance in subjects' control was accounted for by the linear transfer functions for all but the tactual condition with the single integrator system. In this condition only about 40% of the variance was accounted for, and there were strong peaks in the spectra at non-input frequencies in the range of 3 to 7 rad/s. Apparently some strongly nonlinear behavior resulted in this condition.

#### Dual-Axis Tracking

A second laboratory study by Burke, Gilson, and Jagacinski<sup>10</sup> compared tracking with visual and KT displays when a secondary visual task was performed concurrently. The primary task required subjects to use their left hands to stabilize a subcritical first-order unstable system. Three different displays were used for this primary task: (1) a one-dimensional quickened KT display; (2) a one-dimensional unquickened visual display; (3) a one-dimensional quickened visual display for which the signal was additionally passed through an off-line KT display. This last visual display condition thus had the same benefit of quickening and the same detriment of the servomotor lag as the KT display condition.

The secondary task required subjects to use their right hands to stabilize a different first-order unstable system. Adaptive circuitry similar to that of Jex, Jewell, and Allen<sup>11</sup> adjusted the time constant of the secondary task, until subjects' time-averaged error on the primary task was 25% higher than when the primary task was performed without significant secondary task loading. The performance measures were the washout-filtered time-averaged error on the primary task and the inverse of the time constant for the secondary task,  $\lambda_s$ . In order to avoid the need for scanning in the

visual-visual display conditions, the primary and secondary displays for these conditions were respectively the vertical and horizontal position of a single dot moving on an oscilloscope screen. For the KT display condition, a single dimensional visual display was used for the secondary task.

The results of this experiment for dual task performance are shown in Fig. 7. The quickened KT display permitted superior performance on both the primary and secondary tasks. In contrast to these results, the quickened KT display and the two primary visual displays yielded equivalent performance when subjects performed only a single-dimensional critical tracking task alone. Therefore, there seems to be some benefit of combining KT and visual displays in dual task performance beyond what one might expect from single task performance. This experimental result is not due to the elimination of visual scanning because the visual displays were integrated into a single moving dot. It may be that using two sensory modalities provides additional attentional resources, additional sensory buffers, and/or additional cue discriminability for processing the displayed signals. Further research is necessary to delimit these possibilities.

One cautionary note should be added concerning the generality of this experimental finding. Preliminary data on dual task tracking of sum-of-sinewaves inputs without crosscoupling of the two tasks has not so far revealed similar superiority of the combination of KT and visual displays. However, these data are still preliminary.

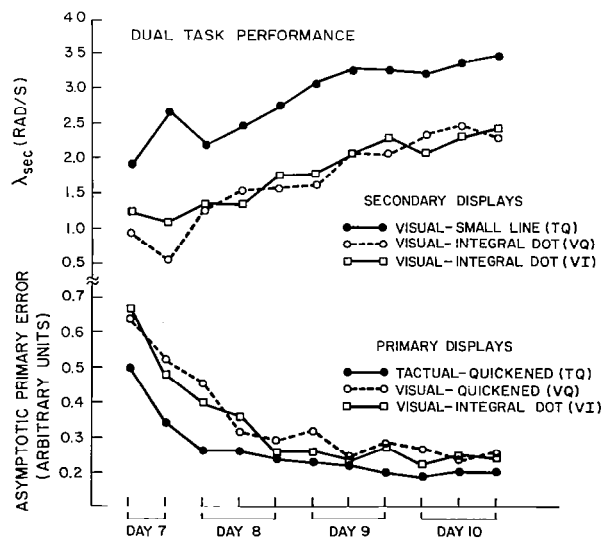


Fig. 7 Mean performance on a dual tracking task. (Copyright 1980, *Ergonomics*, Vol. 23, p. 970)

### Recommendations

In summarizing the single axis tracking results with the KT display, it is helpful to consider separately the quickened and unquickened displays. The quickened displays may be considered analogous to command displays, whereas the unquickened displays are analogous to situation displays used in helicopters. With the quickened displays, the subjects approximated a lag, and tracking performance with the KT display was equivalent to that obtained with a visual display for a low frequency sum-of-sinewaves input. On the critical tracking task, the quickened visual display was superior to the quickened KT display. However, the results of Burke et al.<sup>10</sup> suggest that this difference is due to the servomotor lag in the implementation of the KT display.

In contrast to these results, the unquickened (situation-like) visual display was superior to the unquickened KT display for both sum-of-sinewaves tracking and critical tracking. With the unquickened displays subjects approximated a proportional element or gain. The present results therefore suggest that the KT display be used with command type displays that permit the tracker to behave in a lag-like manner. Under these conditions the KT servomotor lag must be carefully designed relative to the anticipated task requirements.

In dual task performance both the simulator and laboratory studies suggest that the combination of KT and visual displays may provide superior overall performance to the use of only visual displays. Part of the advantage of the KT display may be due to a reduction in visual scanning. Additionally, the use of a second sensory modality may provide some sensory and/or cognitive advantages over a single modality. However, these results need to be carefully tested for their generality beyond particular laboratory tasks. Full scale simulator studies and/or inflight testing appear to be warranted in light of the promising nature of the present findings.

### Acknowledgement

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